

Finger dexterity, skin temperature, and blood flow during auxiliary heating in the cold

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Brajkovic, Dragan, and Michel B. Ducharme. Finger dexterity, skin temperature, and blood flow during auxiliary heating in the cold. *J Appl Physiol* 95: 758–770, 2003. First published May 2, 2003; 10.1152/jappphysiol.00051.2003.—The primary purpose of the present study was to compare the effectiveness of two forms of hand heating and to discuss specific trends that relate finger dexterity performance to variables such as finger skin temperature (T_{fing}), finger blood flow (Q_{fing}), forearm skin temperature (T_{fak}), forearm muscle temperature (T_{mus}), mean weighted body skin temperature (T_{sk}), and change in body heat content (ΔH_b). These variables along with rate of body heat storage, toe skin temperature, and change in rectal temperature were measured during direct and indirect hand heating. Direct hand heating involved the use of electrically heated gloves to keep the fingers warm (heated gloves condition), whereas indirect hand heating involved warming the fingers indirectly by actively heating the torso with an electrically heated vest (heated vest condition). Seven men (age 35.6 ± 5.6 yr) were subjected to each method of hand heating while they sat in a chair for 3 h during exposure to -25°C air. Q_{fing} was significantly ($P < 0.05$) higher during the heated vest condition compared with the heated gloves condition (234 ± 28 and 33 ± 4 perfusion units, respectively), despite a similar T_{fing} (which ranged between 28 and 35°C during the 3-h exposure). Despite the difference in Q_{fing} , there was no significant difference in finger dexterity performance. Therefore, finger dexterity can be maintained with direct hand heating despite a low Q_{fing} . ΔH_b , T_{sk} , and T_{mus} reached a low of -472 ± 18 kJ, $28.5 \pm 0.3^\circ\text{C}$, and $29.8 \pm 0.5^\circ\text{C}$, respectively, during the heated gloves condition, but the values were not low enough to affect finger dexterity.

body heat content; heated gloves; indirect vasodilation; body temperature; torso heating

EXPOSURE OF THE FINGERS TO cold can decrease finger dexterity and, as result, increase work-related accidents (15). The use of direct hand heating (e.g., electrically heated gloves) or indirect hand heating [i.e., increasing body heat content (H_b) by actively heating another region of the body, such as the torso, in an attempt to vasodilate the extremities] are two methods that have been successfully used in past studies to increase finger comfort and to prevent dexterity decrements during work in the cold (2, 4, 28). The primary

purpose of the present study was to compare the effectiveness of each method in maintaining finger dexterity and to discuss specific trends that relate finger dexterity performance to variables such as finger skin temperature (T_{fing}), finger blood flow (Q_{fing}), forearm skin temperature (T_{fak}), forearm muscle temperature (T_{mus}), mean weighted body skin temperature (T_{sk}), and change in H_b (ΔH_b).

In relation to finger dexterity performance, Clark (7) found that it was hindered when hand skin temperature (T_{hand}) fell to 13°C but was unaffected when T_{hand} was 16°C ; unfortunately, Clark did not specify what sites on the hand were used to measure T_{hand} . Gaydos and Dusek (17), however, found no decrement in finger dexterity at a T_{fing} of 16 – 18°C , but a significant performance decrement was observed at a T_{fing} of 10 – 13°C .

Past studies have also suggested that finger dexterity may be more dependent on Q_{fing} compared with T_{fing} (8, 29). The suggestion is based on experiments that examined finger dexterity performance during different rates of hand cooling and other studies that examined the effect of whole body cooling while the hands were kept comfortable. These studies are examined in more detail below.

Rate of hand cooling. Clark and Cohen (8) examined the effects of the rate of cooling of the hands on manual performance by having each subject insert his hands in either a -18 or -7°C cold box while the rest of his body was exposed to 24°C air. They found that at a T_{hand} of 7°C , the slower rate of hand cooling resulted in a significantly greater decrement in performance compared with the faster rate of cooling. Mills (29) also did a similar experiment that produced similar findings. These studies suggest T_{fing} is not the most accurate indicator of finger dexterity. Lockhart and Kiess (28) and Teichner (33) also found that there was not always a strong association between finger dexterity performance and T_{fing} during cold exposure.

Cooling the body while the hands are kept warm. The suggestion that other factors other than T_{fing} may be more accurate indicators of finger dexterity is also supported by studies that examined the effects of body cooling on finger dexterity while the hands were kept

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comfortable in a hand warming box (24, 27). Lockhart (27), for example, did an experiment in which block stringing and Perdue pegboard (PP) performance were done at two T_{sk} levels (26 and 21°C) during both a slow (90-min cooling period) and fast rate of body cooling (15-min cooling period). During the whole body cooling, the hands were kept "well above T_{hand} values associated with decremental performance." Performance decrements only occurred during the lower T_{sk} of 21°C and slow rate of cooling (90-min cooling period). During whole body cooling, the blood flow in the extremities is decreased to conserve whole body heat. Therefore, the decreased dexterity observed with the lower T_{sk} and slow rate of cooling may have been due to the lower level of blood flow in the extremities in that particular condition.

In all of the above studies, $\dot{Q}_{fing}$ and T_{fing} were not actually measured. Ducharme et al. (12) did measure $\dot{Q}_{fing}$ during dexterity performance evaluation and found that during whole body cold exposure, finger dexterity can be decreased even at a T_{fing} of 15–18°C, if $\dot{Q}_{fing}$ is low. Therefore, they suggested that $\dot{Q}_{fing}$ may be a better indicator of finger dexterity during cold exposure, compared with T_{fing} . However, a T_{fing} of 15–18°C is too close to the T_{fing} at which dexterity decrements have been observed in the past (i.e., T_{fing} of 10–13°C). Therefore, to have a better assessment of the effect of a low $\dot{Q}_{fing}$ on finger dexterity without any possible contribution from a low T_{fing} , it would be appropriate to maintain the fingers at a higher, more comfortable temperature [e.g., $T_{fing} > 23^\circ\text{C}$; because Havenith et al. (19) found that the onset of pain can occur with a contact skin temperature between 14 and 23°C]. Brajkovic and Ducharme (2) did exactly that in a study in which finger dexterity was measured while T_{fing} was kept high (31–35°C) and $\dot{Q}_{fing}$ was low [27 ± 5 perfusion units (PU); PU is a relative unit of blood flow measurement] to understand the importance of $\dot{Q}_{fing}$ on finger dexterity. Ferris et al. (16) did a similar study, but, unfortunately, they did not measure finger dexterity.

The Brajkovic and Ducharme (2) study found that finger dexterity was not decreased relative to another condition in which T_{fing} and $\dot{Q}_{fing}$ were both high (31–35°C and 255 ± 19 PU, respectively). However, the finger dexterity (PP test) sessions used did not last for more than 3–4 min. Therefore, the present study was designed to determine the importance of $\dot{Q}_{fing}$ on maintaining finger dexterity during prolonged work (two 30-min sessions) in the cold (-25°C air) by examining the effectiveness of direct hand heating (using electrically heated gloves) and indirect hand heating (indirectly heating the hands by actively heating the torso) over time. It is the first study to measure T_{fing} , $\dot{Q}_{fing}$, and finger dexterity simultaneously during prolonged work sessions in the cold so that, unlike past studies, no assumptions have to be made about any of the three variables.

The present study also includes other physiological measurements that have been shown to affect finger dexterity such as T_{fing} and T_{mus} (25), T_{sk} (24, 26, 27),

and ΔH_b (4). All these data will be used to provide a more complete picture of the physiological responses occurring in the body in an attempt to determine the key physiological mechanisms that may be responsible for cold-induced dexterity decrements observed during prolonged work in the cold. The inclusion of these variables may be used to explain any differences or similarities that may exist between conditions that cannot be explained by the T_{fing} and/or $\dot{Q}_{fing}$ responses observed.

It is hypothesized that during prolonged work (as defined in this study), finger dexterity will decrease over the course of 3 h during direct hand heating, whereas no decrement in performance will occur with indirect hand heating, despite a similar T_{fing} . The difference in dexterity performance will be attributed to the lower $\dot{Q}_{fing}$ and lower T_{mus} that will occur during the direct hand heating condition as a result of a significantly greater decrease in H_b .

METHODS

Subjects. Seven healthy, nonsmoking male volunteers with the following characteristics were recruited: age 35.6 ± 5.6 (SD) yr, height 178.0 ± 2.3 cm, weight 85.9 ± 7.1 kg, and body surface area 2.04 ± 0.08 m². Body surface area was calculated by using the formula of DuBois and DuBois (11). All subjects were medically screened by a physician at Defence Research and Development Canada-Toronto (DRDC-Toronto) before being asked for their written consent. This study was approved by the Human Research Ethics Committee at DRDC-Toronto.

Hand heating conditions. Subjects were exposed to two different hand heating conditions that involved direct and indirect hand heating. Each cold exposure was initiated at ~10 AM each morning. During the direct hand heating condition, the hands were actively heated with thin, electrically heated gloves and Arctic mitts were worn over the gloves. This condition was designated as the heated gloves condition. During the indirect hand heating condition, an electrically heated vest was used to indirectly heat the hands by increasing the H_b (the vest was worn but not powered during the heated gloves condition). This condition was designated as the heated vest condition. The hands were insulated with nonpowered electrically heated gloves and Arctic mitts. During the heated gloves and heated vest conditions, the Arctic mitts were removed during two 30-min finger dexterity sessions that were done at 30–60 min (*dexterity test 1*) and 135–165 min (*dexterity test 2*) of the 180-min cold exposure.

Ambient condition and clothing worn. The experimental sessions were done 1 wk apart over a time period spanning from August to October. Subjects sat in a chair while exposed to an ambient temperature of $-25 \pm 1^\circ\text{C}$ for 3 h during both tests. The wind speed was 2 km/h.

The subjects wore all three layers of the Improved Environmental Clothing System Canadian Forces (CF) Arctic clothing ensemble (3.6 clo, $0.556 \text{ m}^2 \cdot ^\circ\text{K} \cdot \text{W}^{-1}$) during the cold exposure. The three-layer system included a fleece garment (first layer), an uninsulated inner parka and pants (second layer), and an insulated outer parka and pants (third layer). A thin pair of long, cotton underwear was worn under the fleece pants. Standard CF mukluks, woolen socks, and a balaclava were also worn. The 3.6-clo Arctic clothing insulation value did not take into account the long, cotton under

wear worn under the fleece pants, which has a clo value of 0.3 ($0.05 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$). The hands were insulated with thin gloves and Arctic mitts for most of the 3-h cold exposure, except during the dexterity tests, when only the thin gloves were worn (see text under *Hand heating conditions* above for more details).

Design of electrically heated vest and gloves. The electrically heated vest consisted of 10 Kapton insulated flexible heaters (Omega Engineering, Stamford, CT) fixed around the torso as follows: two heaters (each $12 \times 20 \text{ cm}$) on the chest, two heaters on the abdomen (each $8 \times 30 \text{ cm}$), one heater at each side of the torso (each $8 \times 20 \text{ cm}$), two heaters over the shoulder area (each $8 \times 30 \text{ cm}$), and two heaters on the back (each $15 \times 30 \text{ cm}$). The heaters covered a total area of 0.266 m^2 . The heaters were not in direct contact with the skin but inside a fire-resistant pocket made of Nomex fabric. In addition, a 1-cm layer of Thinsulate insulation was placed inside the pocket on the outer surface of the heater. The Thinsulate insulation was covered by a piece of reflective Mylar to help reflect the radiative heat back to the torso. Once the heaters were placed inside the pockets, the pockets were sewn together to form a vest that covered a total area of 0.366 m^2 . A tight, short-sleeved Lycra body suit that extended down to the midhigh level was worn over the heaters to optimize the contact between the skin and the heaters.

Preselected voltages were sent by five current-limiting power supplies (two model 6030A, 0-200V/0-17A, 1000W; three model 6034A, 0-60V/0-10A, 200W; Hewlett Packard) to the five pairs of heaters to achieve a skin temperature of $42 \pm 0.5^\circ\text{C}$ under each heater. The power supplies were controlled by a computer that allowed the user to input the desired voltage for each pair of heaters in the electrically heated vest. To ensure that the skin temperature under the heaters did not reach 45°C at any time, the computer turned off the heater completely if skin temperature reached 44°C . The threshold for cutaneous burns occurs at a skin temperature of 45°C when heating is applied for 2-3 h (30).

The electrically heated gloves used were constructed by using a 300-strand tinsel wire that was knitted into a tight-fitting, nylon glove (Rapier Missile Glove, Vacuum Reflex, Suffolk, UK). The heating wire of each glove surrounded each finger and partially covered the back of the hand. The palms were not heated.

Physiological variables measured. During the 3-h cold exposure, the following physiological variables were measured: T_{ring} was measured by using a cylinder-shaped thermistor [$1.9 \times 8.6 \text{ mm}$; Baxter 400 series rectal/esophageal probe without the protective sheath covering (time constant = 0.9 s in well-stirred water), Baxter Healthcare, Deerfield, IL]. A probe was placed on the pad of the "ring" fingertip of each hand. It was held in position on the skin with double-sided adhesive tape (3M Double-Stick Discs, 3M Medical Division, St. Paul, MN) and with surgical tape (3M Transpore Tape, 3M Canada, London, ON, Canada), without constricting the finger. Toe skin temperature (T_{toe}) was measured by using a DRDC-Toronto laboratory-made, banjo probe (diameter = 10.2 mm, maximum height = 4.7 mm) that contains a protruding YSI 44004 thermistor bead (Yellow Springs Instruments, Yellow Springs, OH). The probe is similar in shape to the YSI 081 standard surface probe, but it has a Plexiglas contact surface (instead of the stainless steel surface used in the YSI probe) and it has a time constant of 5 s in well-stirred water. A probe was placed on the lateral side of the big toe of each foot. The toe thermistor was held in place against the skin with surgical tape (3M Transpore Tape, 3M Canada). Rectal temperature (T_{re}) was measured via a thermistor (Pharmaseal 400 series, Baxter) inserted 15 cm beyond the

anal sphincter. The T_{re} data were normalized, and the change in rectal temperature (ΔT_{re}) during the exposure was reported. Measurements of T_{ring} , T_{toe} , and T_{re} were made five times per minute over the course of 3 h with a data-acquisition system (model 3497A data acquisition/control unit; Hewlett Packard). An average value was printed out each minute.

Q_{ring} was measured with a 780-nm laser-Doppler flowmeter probe (model 414 small-angled laser Doppler probe, Perimed, Stockholm, Sweden) that was connected to a laser Doppler microvascular perfusion measurement unit (model PeriFlux 4001 Master, Perimed). A blood flow probe was placed next to each T_{ring} thermistor. The probe was held in place with a plastic holder (model PH 14, Perimed). The plastic holder was trimmed so that only a 2-mm edge surrounded the probe housing, and hence less plastic covered the fingertip. It was held in position on the skin with double-sided adhesive tape (3M Double-Stick Discs, 3M Medical Division) and with surgical tape (3M Transpore Tape, 3M Canada), without constricting the finger. The unit of measurement used to represent the skin blood flow is the PU. A calibration standard is used to adjust the laser-Doppler flowmeter readings to coincide with the readings obtained with Perimed's Motility Standard. Q_{ring} was measured 15 times per minute for 3 h, and an average Q_{ring} was taken every minute.

T_{mus} was measured with a sterilized multicouple probe (OD 0.9 mm; time constant of 0.25 s in well-stirred water) (13), which was inserted in the flexor carpi radialis muscle at a depth of 1.5 cm and a distance of $\sim 9 \text{ cm}$ distally from the medial epicondyle in the bulk of the muscle. The insertion of the temperature probe into the forearm muscle was performed by a physician. The skin above the muscle was disinfected with iodine solution and then anesthetized with 2% Xylocaine (2.0 ml). A sterilized catheter (18 gauge) was introduced perpendicularly into the muscle at a depth of 1.5 cm. The sterilized multicouple probe was then inserted through the catheter into the muscle after which the catheter was carefully withdrawn. Both the catheter and multicouple probe were marked with a pen to indicate the 1.5-cm insertion limit. To prevent the multicouple probe from sliding out of the puncture site, the probe was taped at the puncture site with Tegaderm tape.

T_{sk} was measured immediately next to the site of the multicouple probe insertion using a heat flux transducers (HFTs) with an embedded thermistor [model HA13-18-10-PC, Concept Engineering, Old Saybrook, CT] at distance of $\sim 7 \text{ cm}$ distally from the medial epicondyle in the bulk of the muscle.

Gas-exchange analyses. Open-circuit spirometry was used to determine oxygen uptake (VO_2 ; in l/min STPD) and carbon dioxide output (VCO_2 ; in l/min STPD) every min for the 3-h cold exposure except during 30-60 and 135-165 min. The metabolic mouthpiece was removed during these times so that the subjects could perform the finger dexterity tests without any arm movement or visual field restrictions. The subjects used a mouthpiece equipped with a T-shaped valve (series 7920, Hans Rudolph, Kansas City, MO) that directed expired gases by means of a 3-m piece of plastic tubing into a 5-liter mixing box located outside the cold chamber. An aliquot of dried expired gases was pumped to O_2 and CO_2 analyzers (models S-3A and CD-3A, respectively, Ametek Instruments, Paoli, PA). VO_2 , VCO_2 , and respiratory exchange ratio (RER) were calculated and printed out every minute. The portion of the plastic tubing that was inside the cold chamber was wrapped with electrical heating tape to prevent any ice buildup inside the hose. A temperature controller was

used to maintain the tape at 43°C. The heating tape was then wrapped with pipe-insulating foam that had 2-cm-thick walls.

Heat balance calculation. Rate of body heat storage (S) was calculated as outlined below. All the variations in the equations are measured in watts.

$$S = M - W - (R + C + K) - E_{\text{sk}} - E_{\text{respir}} - C_{\text{respir}}$$

where M is metabolic rate, W is rate of work, $R + C + K$ are radiative, convective, and conductive heat flows, respectively, E_{sk} is evaporative heat loss from the skin, E_{respir} is evaporative respiratory heat loss, and C_{respir} is convective respiratory heat loss.

ΔH_t was also calculated. The minute-by-minute S data were converted to a value in joules. ΔH_t represents the change in H_t at time t (in min) from the initial H_t at 0 min. ΔH_t (in kJ) was calculated as follows:

The S value reported in watts on a minute-by-minute basis was represented in terms of kilojoules per minute by using the formula

$$S \text{ (kJ/min)} = S \text{ (W)} \cdot 60 \cdot 1,000$$

The ΔH_t from one minute to the next was calculated by using the following formula (except at 0 min, where ΔH_0 (kJ) = H_0 (kJ))

$$\Delta H_t = \Delta H_{t-1} + S_t$$

These data were then normalized so that $\Delta H_0 = 0$, and the following formula was used to track ΔH_t over the course of the 3-h session relative to 0 min

$$\Delta H_t = \Delta H_t - \Delta H_0$$

The ΔH_t during the 30-min dexterity tests was estimated based on a constant S that was determined by taking the average S value calculated 5 min before and 5 min after the 30-min dexterity test sessions.

M was measured by using the following formula

$$M = 3520.23 \cdot \text{KEE} + 0.771 \cdot V_{O_2} \quad (31)$$

where V_{O_2} is expressed in liters per minute (l/min), W was equal to zero because subjects sat in a chair for the entire 3-h cold exposure.

$R + C + K$ were measured by using heat flux transducers (HFTs) with embedded thermistors (model HA13-16 10-PFC, Concept Engineering). The mean body heat flux (in W/m^2) for each subject was multiplied by the surface area of the subject (in m^2) to determine the mean body heat flow in watts. The HFTs were recalibrated, and the values were corrected for the depressed heat flux measurement that occurs due to the thermal resistance of the HFTs (14).

The HFTs were placed on the body as described in Brayton et al. (34) by using a modified version of the thermistor sites used by Hardy and DuBois (16). Ten HFTs were used to represent the heat flux of the heated portion of the body, and 10 HFTs were used to represent the unheated regions of the body. The heat flux and skin temperature weighting coefficients for the torso region originally used in the Hardy and DuBois system were modified to represent the heated and unheated areas of the torso. The "heated region of torso coefficient" ($\text{Coeff}_{\text{torso,heated}}$) for each subject was calculated by dividing the wet area (0.266 m^2) by the entire body surface area (in m^2). Once the $\text{Coeff}_{\text{torso,heated}}$ was calculated, the front and back "unheated region of torso coefficients" ($\text{Coeff}_{\text{torso,unheated}}$) for each subject were calculated in the following manner

$$\text{Coeff}_{\text{torso,unheated}} = (0.35 - \text{Coeff}_{\text{torso,heated}})/2$$

where 0.35 is the Hardy and DuBois coefficient used to represent the torso area.

E_{respir} was calculated by using the following formula

$$E_{\text{respir}} = \rho \cdot k \cdot V_R \cdot (W_{\text{respir}} - W_A) \quad (5)$$

where ρ represents the density of air (STPD) = 0.001293 kg/l , k represents the latent heat of vaporization = $675 \text{ W} \cdot \text{h}^{-1} \cdot \text{kg}^{-1}$, V_R represents the expired air volume (in l/h STPD), W_{respir} represents the humidity ratio of expired air (in $\text{kg water/kg dry air}$), and W_A represents the humidity ratio of ambient air (in $\text{kg water/kg dry air}$). W_{respir} was calculated by using the following formula

$$W_{\text{respir}} - W_A = 0.622 \cdot (P_{\text{respir}} - (101.325 - P_A)) / (P_A - (101.325 - P_A))$$

where P_{respir} (in kPa) represents the saturated vapor pressure of the expired air = 100% saturation at 29.6°C = 4.14 kPa (5) and P_A (in kPa) represents the vapor pressure of the ambient air = 100% saturation at 25°C = 0.08 kPa . C_{respir} was calculated by using the following formula

$$C_{\text{respir}} = \rho \cdot V_R \cdot (T_{\text{respir}} - T_A) \cdot (c_{p,\text{air}} + c_{p,\text{water}} \cdot W_A) \quad (5)$$

where V_R is expressed in liters per hour (STPD), T_{respir} represents the expired air temperature = 29.6°C (5), T_A represents the ambient temperature = -25°C , $c_{p,\text{air}}$ represents the specific heat of dry air = $0.28 \text{ W} \cdot \text{h}^{-1} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$, $c_{p,\text{water}}$ represents the specific heat of water vapor = $0.52 \text{ W} \cdot \text{h}^{-1} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$, and W_A (in $\text{kg water/kg dry air}$) = $0.622(P_A/101.325 - P_A)$, where P_A is expressed in kilopascals.

E_{sk} was estimated from a model developed by Cain and McLellan (6). The model used vapor pressure readings obtained with six humidity sensors that were positioned at -5 and 15 mm above the skin surface (i.e., each sensor was inside a plastic housing that was placed on the skin (sensor 5 mm from skin surface) and on the first layer of clothing (sensor 15 mm from skin surface)) at three different locations on the body. A temperature thermistor was attached to each humidity sensor. Two humidity sensors were placed on the lateral side of the right calf, two sensors were placed on the anterior side of the left thigh, and two sensors were placed on the lateral side of the right upper arm. The water vapor pressure at the skin was predicted from the water vapor measurements provided by the sensors in the clothing. This was, in turn, used in calculating E_{sk} . The model was viewed as one-dimensional flow of water vapor through the multiple layers of Arctic clothing, which produced resistance to the flow.

Finger dexterity tests. During 30–60 min (dexterity test 1) and 135–165 min (dexterity test 2), subjects alternated between two dexterity tests [a C-7 rifle disassembly and assembly test (3- to 4-min duration) and three PP tests (3- to 4-min duration)] during each 30-min test session. The Arctic mitts were removed during the dexterity tests; however, the thin gloves were still worn.

The gloves do decrease dexterity performance (by up to 60%) compared with performance of the tasks barehanded (based on a previous study in which the same hand insulation was worn (4)), but because the same gloves were worn in both conditions, a comparison of finger dexterity can be made between the two conditions. In addition, it has been shown in a past study (4) that a significant degradation (up to 45%) in fine finger dexterity performance (on the basis of PP scores) can occur, even when thin gloves are worn, if the fingers are cooled to an uncomfortable temperature ($9.4 \pm 0.5^\circ\text{C}$).

Dexterity test 1 was not done until the 30-min mark because an objective of the study was to calculate $\dot{S}$ before and after each dexterity test when mean vest heat flow ($\dot{H}_{\text{vest}}$) was relatively stable and mean skin temperature under the heating vest stabilized at $42 \pm 0.5^\circ\text{C}$. $\dot{H}_{\text{vest}}$ and skin temperature under the vest were stable 15–25 min after the vest was first turned on (0 min). Therefore, the 25- to 30-min window was used to calculate $\dot{S}$ when $\dot{H}_{\text{vest}}$ was stable, and it gave a good assessment of $\dot{S}$ just before the initiation of the dexterity test. $\dot{S}$ could not be calculated during the dexterity tests because metabolic data were not collected during the two 30-min work sessions because the mouthpiece interfered with proper task performance. *Dexterity test 2* was done at 135–165 min, instead of 150–180 min, so that a 15-min period was available after the dexterity test to calculate $\dot{S}$.

The C-7 rifle task was chosen because it was representative of the type of finger dexterity task that might be carried out by soldiers in the field. It was used as a measurement of gross finger dexterity. Subjects were required to do a "detailed stripping" of the rifle as outlined in "The Warrior" Canadian Forces combat survival manual (10). This involves an eight-step "field strip" (step 9 was omitted for this experiment) and a six-step "detailed strip" (step 3 was omitted for this experiment). A total of 10 pieces (primarily made from metal) were disassembled. The process was then repeated in the reverse order to reassemble the C-7 rifle. The PP test, on the other hand, is an extensively used fine finger dexterity test, which has been shown to be a reliable and valid measure of finger dexterity over the years (1, 34). The PP consists of a pegboard with two columns of small holes down the middle of the board and four small cups along the top of the board that contain small metal pins, washers, and collars. The object of the PP test is to put together as many assembled units as possible in a 1-min period (1 assembled unit consists of pin, washer, collar, washer). The subjects were asked to perform three trials of the 1-min test with an ~15- to 30-s break between each trial. A PP score was recorded for each trial. In calculating the PP score, the subject was awarded one point for each piece (i.e., pin, washer, or collar) placed on the PP board. The average of the three PP scores are shown in RESULTS. During both hand heating conditions, the Arctic mitts were removed, but the thin knitted gloves were kept on for the duration of the dexterity tests.

The subjects were taught how to do the C-7 test and the PP test by the investigators during a 45-min training session that was arranged with the subject before the start of the experimental sessions. In addition to the training session, during the experimental sessions, the subjects were asked to practice the C-7 and PP tests before each entry into the cold chamber. The practice session took place ~45 min before the subject entered the cold chamber; therefore, it is unlikely that the activity period had any major residual effect on the subsequent cooling period. The subjects practiced the tests until a plateau in performance was observed. A plateau was defined as test scores/times that were equivalent to the best scores/times achieved by the individual in the past (i.e., during the 45-min training session). This often occurred after two to three trials (which is equivalent to disassembling and assembling the rifle a total of 4 to 6 times, because each trial consisted of 2 complete rifle disassemblies and assemblies). Therefore, because each trial took ~3–4 min, the total time spent on practice was 6–12 min. Some subjects reached a plateau in performance faster than others. Therefore, there was not a fixed period of time spent on practice, but rather it was based on the time it took subjects to achieve their personal best scores/times.

The subjects practiced the tests outside the cold chamber while wearing the same Arctic parka worn inside the cold chamber, but they were exposed to a $23 \pm 2^\circ\text{C}$ ambient environment (while a fan was directed at their face and torso). Only shorts covered the lower body during the practice session to help alleviate subject thermal discomfort. Subjects reported feeling "warm, but fairly comfortable" [a rating of 8, based on the McGinnis thermal comfort 13-point scale (23)] upon starting the 3-h cold exposure in the cold chamber at $-25 \pm 1^\circ\text{C}$.

In addition to wearing the Arctic parka outside the cold chamber, the laser-Doppler probe plastic holder (see *Physiological variables measured* earlier in METHODS for further details) was taped onto the pad of the ring finger of each hand during the practice sessions so that subjects became comfortable with doing the dexterity tasks with the probe in place. The laser-Doppler probe did not interfere with the tasks performed because the C-7 rifle task predominately involved using the thumb, the index finger, and the middle finger. Occasionally, all the digits were used to hold onto a larger piece of the rifle, but for the most part the disassembly and assembly of the smaller pieces of the rifle involved using only the digits mentioned earlier. During the PP test, only the thumb and index finger or only the thumb and middle finger were used, depending on the subject's preference, but for the sake of consistency, the same two digits were used for both conditions.

Criteria used to terminate a cold chamber session. The experiment was terminated before 3 h if any of the following conditions were observed: 1) T_{re} reached 35.5°C ; 2) T_{fing} or T_{toe} reached 5°C ; 3) skin temperature on the torso reached 44°C ; 4) dizziness, nausea, or fainting precluded further exposure; 5) subject asked to be removed from the cold chamber; or 6) experimenters requested the termination of the exposure.

Statistical analyses. A two-way ANOVA for repeated measures was used to compare the heated gloves and heated vest conditions. The independent variables were "type of hand heating" and "time." This analysis was done for the dependent variables C-7 rifle time, PP score, T_{fing} , Q_{fing} , T_{toe} , T_{sk} , ΔT_{re} , ΔHb , T_{toe} , and $\dot{S}$ from 0 to 180 min. Five-minute averages were calculated for the 180 min of data so that time 2, 7, 12 min, etc. represented the data from 0 to 4 min, 5 to 9 min, 10 to 14 min, and so forth. Five-minute averages were not calculated for the finger dexterity data (i.e., C-7 rifle time and PP score), but instead, each observation was included in the analyses. Results were considered statistically significant at $P \leq 0.05$ (using the Greenhouse-Geisser adjustment for repeated measures). A Newman-Keuls post hoc test was used to determine whether there was a significant difference in any of the dependent variables from 2 to 177 min. All values are presented as means $\pm$ SE.

RESULTS

The cold exposure session was terminated early for two subjects during the heated gloves condition (at the 144- and 149-min marks) because T_{toe} reached 5°C (DRDC-Toronto human ethics criteria for terminating an experimental session). The decrease in n from $n = 7$ to $n = 6$ has not been presented in any of the graphs for the sake of simplicity and neatness (because the drop out between the two subjects was only 5 min apart). This explains the $n = 7$ to $n = 5$ drop at 144 min on each graph presented in this paper.

Unlike the other variables reported, the $\dot{Q}_{\text{fing}}$ data are based on an $n = 6$ and $n = 4$ during the 3-h exposure. $\dot{Q}_{\text{fing}}$ is presented with one less subject because of the data deletion that occurred during one session as a result of equipment failure.

Mean T_{fing} . For the most part, T_{fing} (see Fig. 1A) was on average $35.3 \pm 0.2^\circ\text{C}$ during the heated vest condi-

tion when the subjects were not doing the dexterity tests. During the dexterity tests, T_{fing} decreased to a mean value of $30.9 \pm 0.9^\circ\text{C}$. During the heated gloves condition, T_{fing} was maintained, on average, at $34.1 \pm 0.4^\circ\text{C}$ during the resting periods, whereas during the dexterity tests, T_{fing} was on average, $29.2 \pm 1.1^\circ\text{C}$. T_{fing} during the dexterity test periods was significantly lower relative to the T_{fing} values observed during the pre-dexterity periods for both conditions.

Mean $\dot{Q}_{\text{fing}}$. During the heated vest condition, $\dot{Q}_{\text{fing}}$ (see Fig. 1B) remained relatively stable at 234 ± 28 PU for the entire 3-h exposure, whereas during the heated gloves condition, $\dot{Q}_{\text{fing}}$ remained relatively stable at 134 ± 32 PU during the first hour and then $\dot{Q}_{\text{fing}}$ decreased gradually, after dexterity test 1, to a low of 33 ± 4 PU by the 127-min mark. It should be noted that the $\dot{Q}_{\text{fing}}$ during the dexterity tests was most likely affected by movement artifacts, although it is hypothesized that the PP test was not affected as much as the C-7 rifle task because the ring finger was not used to pick up the different pieces and place them on the board. Overall, $\dot{Q}_{\text{fing}}$ was significantly higher during the heated vest condition after the 5-min mark and it remained significantly higher for the rest of the exposure. Notice that there was a significant difference in $\dot{Q}_{\text{fing}}$ between the two conditions even though the T_{fing} was similar between the two conditions.

Mean T_{toe} . Upon entering the chamber, the subjects did not show any significant difference in T_{toe} between the heated vest and heated gloves conditions (T_{toe} of 28.9 ± 0.9 and $31.1 \pm 0.7^\circ\text{C}$, respectively). During the heated vest condition, T_{toe} remained relatively stable at $30.5 \pm 0.9^\circ\text{C}$ during the 3-h exposure. During the heated gloves condition, T_{toe} gradually decreased to $8.0 \pm 0.4^\circ\text{C}$ by 180 min. T_{toe} during the heated vest condition was significantly higher relative to the heated gloves condition after 22 min.

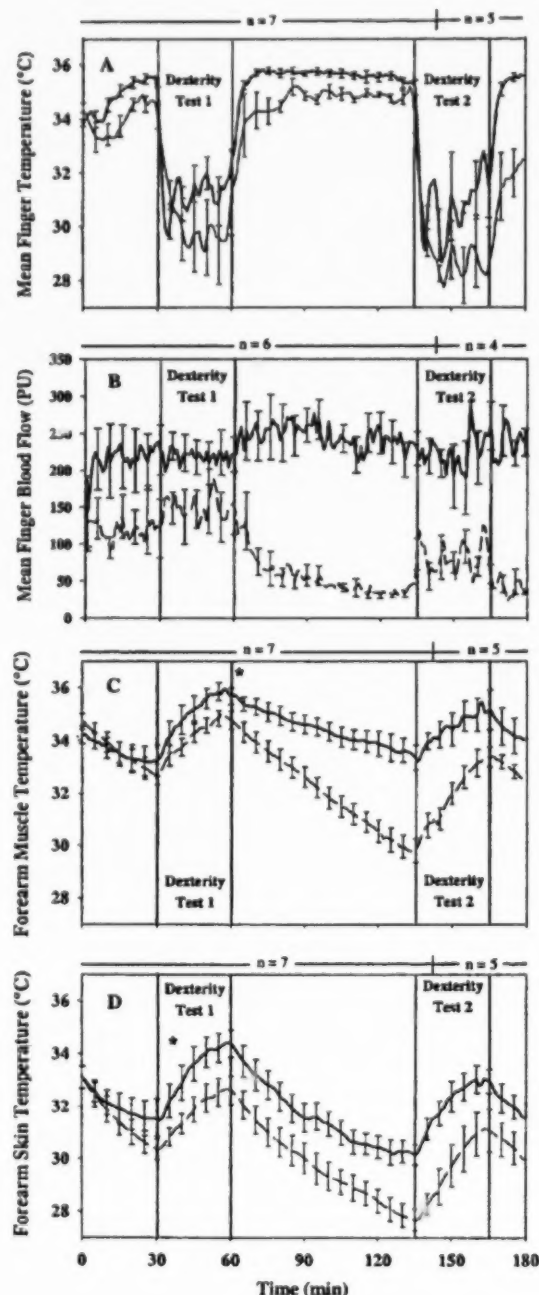


Fig. 1. Mean finger temperature (A), mean finger blood flow (B), forearm muscle (flexor carpi radialis muscle) temperature (C), and forearm skin temperature (D) for the heated vest (solid line) and heated gloves (dashed line) conditions during exposure to -25°C air. A: values are means $\pm$ SE for $n = 7$ or 5 , as indicated. Mean finger temperature was significantly ($P < 0.05$) higher overall from 0 to 180 min during the heated vest condition compared with the heated gloves condition. B: values are means $\pm$ SE for $n = 6$ or 4 , as indicated. Two subjects dropped out at 144 and 149 min, respectively, but for a neater presentation, only data for $n = 6$ and $n = 4$ (starting at 144 min) are presented. Data are presented with 1 fewer subject (compared with other figures) because of the data deletion that occurred during 1 session as a result of equipment failure. Mean finger blood flow was significantly ($P < 0.05$) higher overall during the heated vest condition during the 3-h exposure. C: a sterilized muticouple probe was inserted to a depth of 1.5 cm and a distance of ~ 9 cm distally from the medial epicondyle in the bulk of the muscle. Values are means $\pm$ SE for $n = 7$ or 5 , as indicated. *First significant difference (at 62 min) between conditions, $P < 0.05$. D: the temperature thermistor was placed at a distance of ~ 7 cm distally from the medial epicondyle in the bulk of the muscle. Values are means $\pm$ SE for $n = 7$ or 5 , as indicated. In A, C, and D, two subjects dropped out at times 144 and 149 min, respectively, but for a neater presentation, only data for $n = 7$ and $n = 5$ (starting at 144 min) are presented. *First significant difference (at 37 min) between conditions, $P < 0.05$. In A–D, solid vertical lines represent the start and end of each 30-min dexterity session.

T_{fms} . During the heated vest and heated gloves conditions, T_{fms} (see Fig. 1C) fluctuated during the 3-h exposure, but overall T_{fms} was similar (heated vest condition) or decreased only slightly (heated gloves condition) at the beginning of the exposure compared with the end of the 3-h session. In both conditions, a significant increase in T_{fms} was observed at the end of each 30-min dexterity test relative to the T_{fms} observed at the start of each test. This increase may be attributed to the increased forearm muscle activity that occurred as a result of performing the dexterity tests. During the heated vest and heated gloves conditions, T_{fms} was on average 34.4 ± 0.5 and $32.7 \pm 0.4^\circ\text{C}$, respectively, during the 3-h exposure. During the heated vest condition, T_{fms} did not decrease below $33.2 \pm 0.6^\circ\text{C}$ at anytime during the exposure, whereas during the heated gloves condition, T_{fms} reached a low of $29.8 \pm 0.5^\circ\text{C}$ by 135 min. There was a significant difference in T_{fms} between the conditions after 62 min. The rates of decrease in T_{fms} from 60 to 135 min were significantly different between the heated vest and heated gloves conditions (0.04 and $0.07^\circ\text{C}/\text{min}$, respectively), when the subjects were at rest. During dexterity test 1, there was a similar rate of increase in T_{fms} ($0.08^\circ\text{C}/\text{min}$) as a result of a similar T_{fms} at the initiation of the test. The rate of increase in T_{fms} during dexterity test 2 was greater in the heated gloves condition ($0.12^\circ\text{C}/\text{min}$) compared with the heated vest condition ($0.08^\circ\text{C}/\text{min}$), but it was still not enough to bring T_{fms} up to the absolute T_{fms} temperature observed during the heated vest condition.

T_{fsh} . During the heated vest and heated gloves conditions, T_{fsh} was on average $32.1 \pm 0.5^\circ\text{C}$ and $30.4 \pm 0.5^\circ\text{C}$, respectively, during the 3-h exposure. During both conditions, changes in T_{fsh} (see Fig. 1D) over the 3-h exposure were in phase with the changes in T_{fms} , although T_{fsh} was $1\text{--}2.5^\circ\text{C}$ lower than T_{fms} during the first hour and as much as $2\text{--}3.5^\circ\text{C}$ lower just before dexterity test 2, when T_{fms} was at its lowest temperature. During the heated vest condition, T_{fsh} did not decrease below $30.2 \pm 0.4^\circ\text{C}$ at any time during the entire cold exposure, whereas during the heated gloves condition, T_{fsh} was above $27.7 \pm 0.4^\circ\text{C}$ during the entire session. Overall, T_{fsh} during the heated vest condition was significantly higher relative to the heated gloves condition after 37 min.

Mean body heat loss. The mean heat loss from the body (H_b) (see Fig. 2A) was significantly higher during the heated gloves condition relative to the heated vest condition. During the heated gloves condition, H_b was on average 145 ± 5 W, with exception of the first 15 min of the 3-h exposure. During the dexterity tests, H_b increased from 10 to 20 W (relative to pre-dexterity values) because of the increased heat loss from the hands that resulted when the large Arctic mitts were removed. During the heated vest condition, H_b was on average 77 ± 6 W during the cold exposure, excluding the first 15 min. The first 15–25 min of the heated vest condition was used to establish a relatively stable skin temperature of $42 \pm 0.5^\circ\text{C}$ underneath the heating vest.

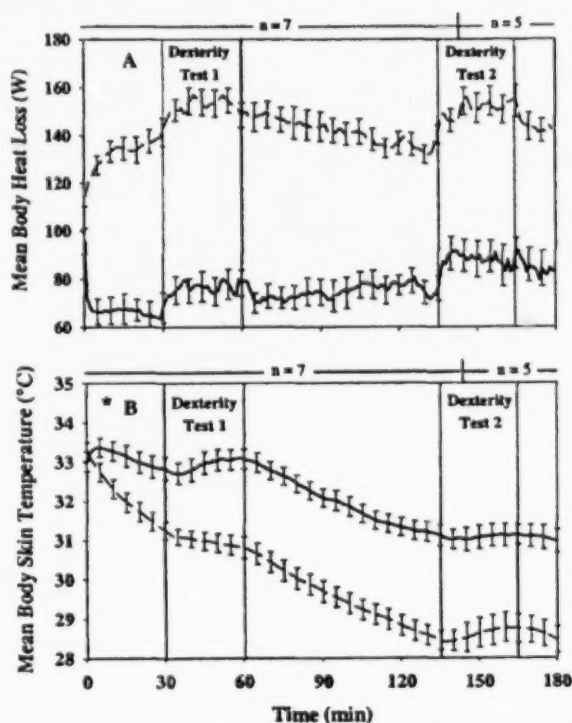


Fig. 2. Mean body heat loss (A) and mean weighted body skin temperature (B) for the heated vest (solid line) and heated gloves (dashed line) conditions during exposure to -25°C air. Values are means $\pm$ SE for $n = 7$ or 5 , as indicated. Two subjects dropped out at 144 and 149 min, respectively, but for a neater presentation, only data for $n = 7$ and $n = 5$ (starting at 144 min) are presented. Solid vertical lines represent the start and end of each 30-min dexterity session. A: mean body heat loss was significantly ($P < 0.05$) higher overall during the heated gloves condition during the 3-h exposure. B: * first significant difference (at 7 min) between conditions, $P < 0.05$.

T_{sk} . Upon entering the chamber, the subjects did not show any significant difference in T_{sk} (see Fig. 2B) between the heated vest and heated gloves conditions (T_{sk} of 33.0 ± 0.3 and $33.3 \pm 0.2^\circ\text{C}$, respectively). By the end of the 3-h exposure, T_{sk} decreased significantly in both conditions. During the heated vest condition, T_{sk} decreased to $31.0 \pm 0.3^\circ\text{C}$, whereas during the heated gloves condition, T_{sk} decreased to $28.5 \pm 0.3^\circ\text{C}$. T_{sk} during the heated vest condition was significantly higher relative to the heated gloves condition after 7 min.

ΔT_{re} . Upon entering the cold chamber, the subjects' T_{re} for the heated vest and heated gloves conditions were 37.23 ± 0.24 and $37.46 \pm 0.36^\circ\text{C}$, respectively, and these two initial temperatures were not significantly different from each other. During the heated vest condition, ΔT_{re} (see Fig. 3A) increased significantly from 0 to $0.17 \pm 0.10^\circ\text{C}$ from 0 to 57 min. ΔT_{re} remained relatively stable from 57 to 118 min and was significantly higher relative to the ΔT_{re} observed at 0 min. At the 118-min mark, ΔT_{re} decreased to a value of

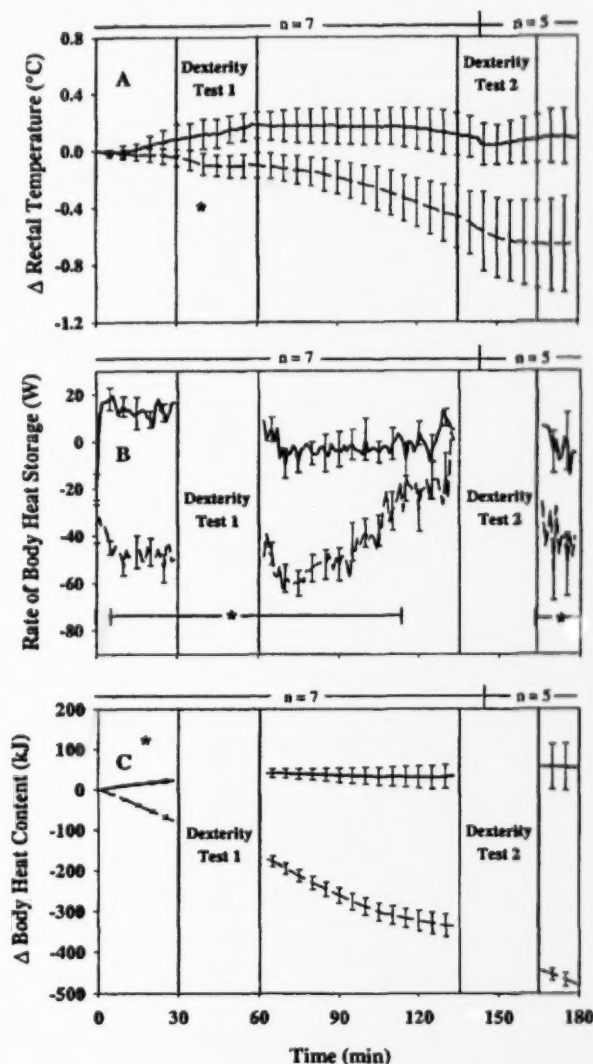


Fig. 3. Change in (Δ) rectal temperature (A), rate of body heat storage (B), and Δ body heat content (C) in the heated vest (solid line) and heated gloves (dashed line) conditions during exposure to -25°C air. Values are means $\pm$ SE for $n = 7$ or 5 , as indicated. Two subjects dropped out at 144 and 149 min, respectively, but for a neater presentation, only data for $n = 7$ and $n = 5$ (starting at 144 min) are presented. Solid vertical lines represent the start and end of each 30-min dexterity session. A: *first significant difference (at 37 min) between conditions, $P < 0.05$. B: *significant difference between conditions (5–115 and 165–180 min), $P < 0.05$. C: *first significant difference (at 17 min) between conditions, $P < 0.05$.

$0.03 \pm 0.15^{\circ}\text{C}$ (relative to 0 min) at 148 min, and finally it increased (although not significantly) to a value of $0.08 \pm 0.20^{\circ}\text{C}$ by time 180 min. The ΔT_{re} by 180 min was not significantly different relative to the ΔT_{re} at 0 min. During the heated gloves condition, the ΔT_{re} of $-0.66 \pm 0.35^{\circ}\text{C}$ after 3 h of cold exposure was significant. There was also a significant difference between the two conditions after 37 min.

$\dot{S}$. During the heated vest condition, $\dot{S}$ (see Fig. 3B) decreased significantly from 18 ± 5 to -3 ± 7 W from 5 to 75 min and the remained relatively stable (average of -2 ± 7 W) until the end of the 3-h exposure. During the heated gloves condition, $\dot{S}$ decreased significantly from -45 ± 3 W to -60 ± 5 from 5 to 75 min and then increased to 0 ± 9 W by 135 min. By the end of the exposure, $\dot{S}$ decreased to -41 ± 11 W. The increase in $\dot{S}$ that occurred during the heated gloves condition after 90 min may be attributed to the mild shivering that was observed in subjects after 90–120 min of cold exposure. There was a significant difference in $\dot{S}$ between conditions from 5 to 115 min but no difference between 115 and 135 min. A significant difference in $\dot{S}$ also existed between 165 and 180 min. $\dot{S}$ data were not presented during the dexterity tests because metabolic data were not collected during these periods.

ΔH_b . During the heated vest condition, ΔH_b (see Fig. 3C) increased (although not significantly) to 54 ± 59 kJ by the end of the 3-h exposure, whereas during the heated gloves condition, ΔH_b decreased significantly to -472 ± 18 kJ after 3 h. There was a significant difference between the two conditions after 17 min. There are no ΔH_b data presented during the dexterity tests because metabolic data were not collected during these periods. The mouthpiece used to collect the subject's expired respiratory gases was removed during each dexterity test so that the tests could be performed without hampering the subject's movements and without obstructing his vision.

PP score. Overall, there was no significant difference in finger dexterity performance between the two conditions, although the scores tended to be consistently higher for the heated vest condition (see Fig. 4A). In addition, for both conditions, there was no significant difference in overall performance between dexterity tests 1 and 2. There were also no significant differences in dexterity performance outside the cold chamber at 23°C compared with performance during any trial inside the cold chamber at -25°C (for both conditions). For each 30-min dexterity test, the PP score increased from trial 1 to trial 3, but the change was not significant. The PP scores outside the cold chamber were 21.3 ± 1.7 and 20.0 ± 1.4 points for the heated vest and heated gloves conditions, respectively. During the heated gloves condition, PP scores for trials 1, 2, and 3 of dexterity test 1 were 17.6 ± 1.2 , 18.7 ± 1.5 , and 20.0 ± 1.7 points, respectively, whereas during the heated vest condition, PP scores were 19.3 ± 1.0 , 21.6 ± 1.6 , and 22.2 ± 1.3 points, respectively. During the heated gloves condition, PP scores for trials 1, 2, and 3 of dexterity test 2 were 19.2 ± 1.9 , 21.5 ± 2.6 , and 21.8 ± 3.2 points, respectively, whereas during the heated vest condition, PP scores were 20.9 ± 1.6 , 23.7 ± 1.1 , and 24.6 ± 1.4 points, respectively.

C-7 rifle task time. Overall, there was no significant difference in finger dexterity performance between the two conditions (see Fig. 4B). In addition, for both conditions, there was also no significant difference in overall performance between dexterity tests 1 and 2. During the heated vest condition, the C-7 rifle task time inside

the cold chamber (-25°C) was similar to the performance observed outside the cold chamber (23°C), with the exception of a significantly higher time (i.e., decreased dexterity) during *dexterity test 1, trial 1* (represented by Δ symbol in Fig. 4B). During the heated gloves condition, the C-7 rifle task time inside the cold chamber (-25°C) was similar to the performance observed outside the cold chamber (23°C), with the exception of a significantly higher time (i.e., decreased dexterity) during *dexterity test 1, trials 1 and 2*, and during *dexterity test 2, trial 1* (represented by * symbol in Fig. 4B). For each 30-min dexterity test, the C-7 rifle time decreased significantly (i.e., dexterity increased) from *trial 1* to *trial 4* (in both conditions). (Note: see DISCUSSION for an explanation of the C-7 rifle task time dexterity results.)

The C-7 rifle task times outside the cold chamber were 175 ± 8 and 164 ± 7 s for the heated vest and heated gloves conditions, respectively. During the

heated gloves condition, the C-7 rifle task times for *trials 1, 2, 3, and 4* of *dexterity test 1* were 203 ± 6 , 179 ± 10 , 164 ± 10 , and 168 ± 9 s, respectively, whereas during the heated vest condition, C-7 rifle task times were 205 ± 9 , 182 ± 11 , 171 ± 10 , and 167 ± 10 s, respectively. During the heated gloves condition, C-7 rifle task times for *trials 1, 2, 3, and 4* of *dexterity test 2* were 187 ± 6 , 171 ± 10 , 157 ± 14 , and 155 ± 7 s, respectively, whereas during the heated vest condition, C-7 rifle task times were 183 ± 11 , 166 ± 10 , 153 ± 5 , and 152 ± 9 s, respectively.

H_{vest} and heater power. During the heated vest condition, H_{vest} decreased relatively rapidly once the electrically heated vest was turned on at 0 min. H_{vest} decreased from -14 ± 1 to -83 ± 2 W during the first 30 min of exposure. The negative heat flow values represent a body heat gain. The first 15–25 min were required to establish a relatively stable skin temperature of $42 \pm 0.5^{\circ}\text{C}$ underneath the heating vest. H_{vest} increased significantly from -83 ± 2 to -74 ± 3 W from 30 to 135 min and then remained relatively stable for the rest of the exposure. During the heated gloves condition, H_{vest} remained stable at 17 ± 1 W from 30 to 180 min. During the heated vest condition, vest heater power remained relatively stable at 111 ± 3 W from 30 to 180 min. During the heated gloves condition, glove heater power was maintained at 33 ± 4 W (for both gloves) and 34 ± 3 W during *dexterity tests 1* and *2*, respectively, whereas in between dexterity tests (65–135 min) glove heater power was maintained at 14 ± 3 W.

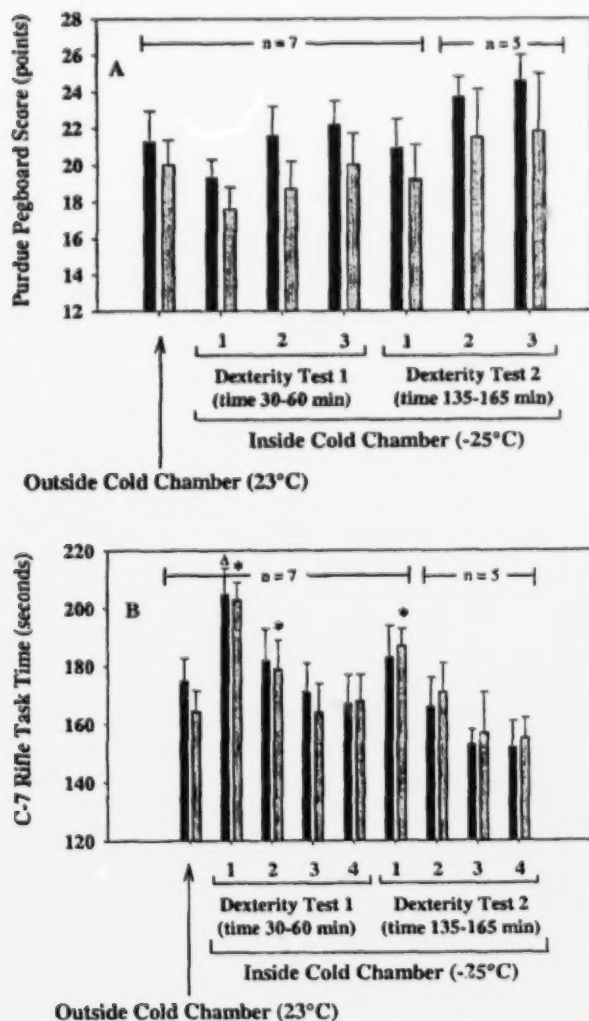


Fig. 4. Purdue pegboard score (A) and C-7 rifle task time (B) for the heated vest (black bars) and heated gloves (gray bars) conditions during *dexterity tests 1* and *2* while subjects were exposed to 23°C and -25°C air. Values are means $\pm$ SE for $n = 7$ or 5 , as indicated. Two subjects dropped out at 144 min and 149 min, respectively, but for a neater presentation, only data for $n = 7$ and $n = 5$ (starting at 144 min) are presented. A: there were no significant ($P < 0.05$) differences between conditions during any of the dexterity trials. In both conditions, there were no significant differences in dexterity performance outside the cold chamber at 23°C compared with performance inside the cold chamber at -25°C (see text under *Finger dexterity tests* in METHODS for details on the clothing worn in each environment). For each 30-min dexterity test, the Purdue pegboard score increased from *trial 1* to *trial 3*, but the change was not significant. For each condition, there was no significant difference in mean Purdue pegboard score between the first 30-min dexterity test and the second 30-min dexterity test. B: there were no significant ($P < 0.05$) differences between conditions during any of the dexterity trials. During the heated vest condition, the rifle task time inside the cold chamber (-25°C) was similar to performance outside the cold chamber (23°C), with the exception of a significantly higher time (i.e., dexterity decreased) during *dexterity test 1, trial 1* (Δ) (see text under *Finger dexterity tests* in METHODS for details on the clothing worn in each environment). During the heated gloves condition, the rifle task time inside the cold chamber (-25°C) was similar to performance outside the cold chamber (23°C), with the exception of a significantly higher time (i.e., dexterity decreased) during *dexterity test 1, trials 1 and 2*, and during *dexterity test 2, trial 1* (*). (See DISCUSSION for a possible explanation of the higher task times observed during the trials mentioned above.) For each condition, there was no significant difference in mean rifle task time between the first 30-min dexterity test and the second 30-min dexterity test.

DISCUSSION

The present study was designed to determine the importance of $\dot{Q}_{\text{fing}}$ in maintaining finger dexterity during prolonged work (two 30-min sessions) in the cold (-25°C air) by comparing the effectiveness of direct hand heating (using electrically heated gloves) with indirect hand heating (using an electrically heated vest) during a 3-h exposure. In addition, finger dexterity performance was compared during prolonged work (i.e., two 30-min sessions) with small and large metal objects while the hands were heated by the direct and indirect methods of hand heating.

Finger dexterity can be maintained despite a minimal blood flow to the fingers. The key finding in this study was that finger dexterity can be maintained during prolonged work in the cold despite a low $\dot{Q}_{\text{fing}}$ as long as T_{fing} remains elevated. Evidence of this may be found by comparing the T_{fing} , $\dot{Q}_{\text{fing}}$, PP score, and C-7 rifle task time results during the direct and indirect hand heating conditions (i.e., heated gloves and heated vest conditions, respectively). T_{fing} , PP score, and C-7 rifle task time were similar between conditions despite a significantly higher $\dot{Q}_{\text{fing}}$ observed during the heated vest condition. Therefore, this finding implies that T_{fing} is a more important indicator of finger dexterity compared with $\dot{Q}_{\text{fing}}$.

It must be noted that during the heated gloves condition, T_{fing} was significantly lower, on average, during the entire 3 h cold exposure. However, from a practical standpoint, the statistically significant differences observed are unlikely to make much of a physiological difference in relation to finger dexterity or comfort because there was a difference of only $1.3 \pm 0.5^{\circ}\text{C}$, on average, between the two conditions during the entire exposure. $\dot{Q}_{\text{fing}}$ may be slightly affected by the small differences in T_{fing} observed in the present study, but it is unlikely to contribute significantly to the large differences in $\dot{Q}_{\text{fing}}$ observed between the two conditions, especially because a past study completed in our laboratory resulted in similar differences in $\dot{Q}_{\text{fing}}$ despite no significant differences in T_{fing} (2).

Short- vs. long-duration dexterity tests: a comparison of results. The data support the finding of an earlier study we did that examined T_{fing} and $\dot{Q}_{\text{fing}}$ in relation to dexterity performance during short (up to ~ 4 min), intermittent periods of work (7 work sessions, 30 min apart) in the cold while comparing passive, direct, and indirect forms of hand heating (2). The earlier study found that finger dexterity is maintained for 3 h during -25°C exposure, despite a low $\dot{Q}_{\text{fing}}$ (27 ± 5 PU during the last hour of exposure), if T_{fing} is maintained at a relatively high temperature (31 – 35°C). However, unlike that past study, the present study has shown that finger dexterity is maintained even during longer (2×30 min) periods of work in the cold. It should also be noted that the level of $\dot{Q}_{\text{fing}}$ observed in the present study during the direct hand heating condition (33 ± 4 PU, just before dexterity test 2) is similar to the $\dot{Q}_{\text{fing}}$ observed during our previous study with similar conditions (2).

In that past study, $\dot{Q}_{\text{fing}}$ was not significantly different during the last hour of cold exposure for the direct hand heating condition compared with a condition in which passive hand insulation (i.e., Arctic mitts and thin nonheated gloves only) was used to slow the cooling rate of the hands. In the passive insulation condition, both T_{fing} and $\dot{Q}_{\text{fing}}$ were relatively stable and low during the last hour at values of $12 \pm 0.5^{\circ}\text{C}$ and 25 ± 5 PU, respectively. Significant decrements in dexterity were found during the passive insulation condition, whereas no dexterity decrements were observed during the direct hand heating condition despite a similar $\dot{Q}_{\text{fing}}$. The similar $\dot{Q}_{\text{fing}}$ values between the passive and direct hand heating conditions in the past study, suggest that in the present study, the relatively low $\dot{Q}_{\text{fing}}$ observed would have resulted in a dexterity decrement if it had not been for the high (28 – 35°C) T_{fing} values maintained during the heated gloves condition.

Examination of physiological variables other than T_{fing} or $\dot{Q}_{\text{fing}}$ in relation to finger dexterity. In relation to the above finding that T_{fing} is a more important indicator of finger dexterity compared with $\dot{Q}_{\text{fing}}$, it is worthwhile considering other factors that have been found to affect finger dexterity before making any general conclusions about the importance of T_{fing} as an indicator of finger dexterity. Some of these factors are discussed below.

T_{sk} , T_{fak} and finger dexterity. If the hands are kept warm (i.e., a $T_{\text{hand}} > 28^{\circ}\text{C}$) finger dexterity decrements can still occur if the body is cooled (24, 26, 27). Decreasing T_{sk} below 24°C alone will decrease finger dexterity (24). In the present study, T_{sk} did not decrease below 31.0 ± 0.3 and $28.5 \pm 0.3^{\circ}\text{C}$ during the heated vest and heated gloves conditions, respectively. Therefore, the dexterity results in both conditions were not affected by a low T_{sk} .

In addition, finger dexterity decrements can still occur if the forearms are cooled, even if the hands are kept comfortable. LeBlanc (25) found that localized forearm cooling (muscle temperature not reported) can significantly decrease finger dexterity (due to the effect of muscle cooling on finger movement) even if the hand is immersed in thermoneutral 33°C water. In the present study, the dexterity results were unlikely to be affected by the relatively high T_{fmus} and T_{fak} observed during both hand heating conditions (T_{fmus} : 33 – 36 and 30 – 35°C during the heated vest and heated gloves conditions, respectively; T_{fak} : 30 – 34 and 28 – 33°C during the heated vest and heated gloves conditions, respectively). It is hypothesized that finger dexterity will most likely decrease, regardless of a high T_{fing} , once T_{fmus} falls below some temperature threshold, which is at least $< 30^{\circ}\text{C}$, because no dexterity decrements occurred in the present study (T_{fmus} was $\geq 30^{\circ}\text{C}$ for both conditions). Heus et al. (21) found that dexterity decrements occur when arm muscle temperature is below 28°C .

Overall, this study found that T_{fing} is a more important indicator of finger dexterity compared with $\dot{Q}_{\text{fing}}$. A relatively high T_{sk} (28 – 33°C) and relatively warm forearm [$(T_{\text{fmus}}$ and T_{fak} of 30 – 36 and 28 – 34°C , respec-

tively) (temperature ranges include both conditions)) may also help to explain the similar finger dexterity performances observed between the direct and indirect hand heating conditions, despite the significantly higher $\dot{Q}_{\text{fing}}$ found during the indirect hand heating condition. The similar dexterity performances occurred despite a considerable difference in ΔH_b (i.e., 54 ± 59 and -472 ± 18 kJ at 180 min, for the heated vest and heated gloves conditions, respectively) between the two conditions.

ΔH_b and the vasodilative response observed in the extremities. The positive ΔH_b value observed during the heated vest condition may be used to explain the relatively high $\dot{Q}_{\text{fing}}$, T_{core} , T_{mus} , and T_{sk} values observed compared with the heated gloves condition. That is, in an attempt to restore body heat balance, the body will vasodilate the extremities to increase heat loss from the body. The positive ΔH_b suggests that the whole body change in heat gain (externally from the heated vest and internally from the metabolic activity of the body) is greater than the overall change in heat loss from the body. Therefore, the different mechanisms of heat loss (sweating, respiratory, conductive, convective) are insufficient to prevent an increase in H_b during the heated vest condition. During the heated gloves condition, however, the heat loss from the body exceeded the heat gain, despite the presence of shivering that slowed down the rate of heat loss during the last 90 min of the cold exposure.

Importance of considering ΔH_b before making conclusions about the effect of T_{sk} on finger dexterity. It is interesting to compare the present study with the study done by Lockhart (27), who examined rate of body cooling on finger dexterity. The experiment involved cooling the body to a T_{sk} of 26 or 21°C during both a slow (90-min cooling period) and fast (15-min cooling period) rate of body cooling. During the whole body cooling, the hands were kept "well above T_{hand} values associated with decremental performance"; unfortunately, T_{hand} values were not reported in the study. Lockhart found that performance decrements only occurred with the lower T_{sk} of 21°C and the slower rate of cooling (i.e., the 90-min cooling period). This finding shows the importance of ΔH_b and T_{mus} on finger dexterity. That is, despite a low T_{sk} of 21°C during the fast rate of cooling, a dexterity decrement did not occur, most likely because there was not enough of a decrease in H_b . Therefore, an insufficient decrease in H_b resulted in a T_{mus} decrease that was insufficient to affect finger dexterity. The Lockhart study suggests that T_{sk} may not be a reliable factor to predict manual performance and that ΔH_b might be a better and more integrated factor.

It is also interesting to note that in the present study, finger dexterity was not affected despite a ΔH_b of -472 ± 18 kJ during the heated gloves condition. This is most likely due to the observation that T_{mus} was 30–35°C, and hence the ΔH_b of -472 ± 18 kJ was not great enough to cool T_{mus} to a temperature at which finger dexterity would be hampered. Rissanen et al. (32) also found manual dexterity was not significantly

affected during cold exposure despite a ΔH_b of -760 ± 67 kJ at the end of the exposure and a low T_{fing} (ranged between 4.4°C and 14.0°C). Rissanen et al. suggested that no dexterity decrement was observed possibly because the series of tasks used were inappropriate and/or that the time to complete the tasks (~2 min) was too short. A third possible explanation, based on the present study, might be that a high T_{mus} may explain the lack of decrement observed, especially because Rissanen et al. stated that the heat debt (calculated using thermometry) was due to cooling of the skin, rather than cooling of the deep body tissues.

Rate of forearm cooling and possible influence of H_b . The rate of decrease in T_{mus} during the heated vest and heated gloves conditions was 0.04 and 0.07°C/min, respectively, from 60 to 135 min when the subjects were at rest. The significantly greater rate of decrease in T_{mus} during the heated gloves condition during this period was most likely due to a lower forearm blood flow as a result of a lower H_b . The rate of increase in T_{mus} during dexterity test 2 was greater in the heated gloves condition (0.12°C/min) compared with the heated vest condition (0.08°C/min), but it was still not enough to bring T_{mus} up to the absolute T_{mus} temperature observed during the heated vest condition. It is hypothesized that if a third dexterity test was performed (60 min after dexterity test 2), T_{mus} would probably have reached a muscle temperature below 28°C (muscle temperature at which dexterity decrements occur (21)) and a dexterity decrement could have been observed. However, in the heated vest condition, T_{mus} was at the same temperature after dexterity test 2 as it was after dexterity test 1. It is hypothesized that T_{mus} would remain at a similar level even after a hypothetical third dexterity test (60 min after dexterity test 2), and finger dexterity would not be hampered. Therefore, indirect hand heating may be better at maintaining finger dexterity compared with direct hand heating during very long cold exposures.

Complex interaction between measured variables and dexterity performance. All of the above findings suggest there is a complex interaction between the various variables that are known to affect finger dexterity (ΔH_b , T_{sk} , T_{mus} , and T_{fing}). In the present study, we found that T_{fing} is a more important indicator of finger dexterity compared with $\dot{Q}_{\text{fing}}$, but it must be noted that this conclusion is based on a ΔH_b , ΔH_b , and T_{mus} that were different between the heated vest and heated gloves conditions being examined. In both conditions, T_{sk} , and T_{mus} were different, but for each variable, the values were high enough that dexterity was not affected, and as a result the effect of a low $\dot{Q}_{\text{fing}}$ on dexterity despite similar T_{fing} could be examined.

In relation to ΔH_b , a past study found that during passive or indirect hand heating finger dexterity was maintained until ΔH_b reached -440 kJ, which corresponded to a T_{fing} of 15°C (4). In the present study, however, T_{fing} was not a concern because the fingers were kept warm (and dexterity was maintained) with electrically heated gloves despite a ΔH_b that was -472 ± 18 kJ; therefore, even though it has been

shown that the fingers cool more rapidly over time when H_b is lower, despite a similar level of clothing insulation (4), it is not known what absolute level of H_b decrease is necessary (when direct hand heating is used) before any significant decrease in finger dexterity occurs.

Explanation of C-7 rifle task time dexterity results. The higher C-7 rifle task times observed during *dexterity test 1* (trial 1, and in one condition, trial 2) and *dexterity test 2* (trial 1), relative to the lower times observed outside the cold chamber, were most likely the result of a learning effect. This hypothesis is based on the observation that the dexterity performances during trials 3 and 4 and, even in most cases, trial 2, were similar to the dexterity performances observed outside the cold chamber. The subjects practiced each dexterity test outside the cold chamber with similar conditions, but the conditions were not identical. Subjects found the extra clothing worn inside the chamber more cumbersome compared with what was worn outside the chamber (see text under *Finger dexterity tests* in METHODS for details about clothing worn). In addition, the angle of the chair and the height of the table used inside the chamber were not identical to the furniture used outside the cold chamber; therefore, the slightly altered sitting posture and limb placement may have affected dexterity performance until the subjects adapted (by trial 2 or 3) to these slightly modified dexterity testing conditions. Therefore, these two factors [1) adapting to the increased bulkiness of the clothing and 2) adapting to the altered posture] may explain the slightly higher rifle task times observed during the first two trials of *dexterity test 1*. The higher C-7 rifle task time observed during *dexterity test 2*, trial 1, likely occurred because the subjects may have become somewhat lethargic and not as motivated after the 1-h rest period between *dexterity tests 1* and 2.

Advantages and disadvantages of indirect hand heating. Indirect hand heating (heated vest condition) has many advantages over direct hand heating (heated gloves condition) despite a similar dexterity performance between the two conditions in the present study. Most notably, the ability to maintain extremity comfort (fingers and toes), finger dexterity, deep core temperature, and body comfort (no shivering observed and most subjects reported feeling "comfortable" or "warm, but fairly comfortable" [on the basis of the McGinnis thermal comfort scale (23)] during the entire 3-h exposure) in the cold (-25°C) while only wearing thin, contact gloves. During the heated gloves condition, some mild, sporadic shivering was observed during the last hour of the 3-h cold exposure; however, shivering may have been suppressed during each of the C-7 rifle tasks and PP tests performed during *dexterity test 2* (135 min–165 min).

Another advantage of indirect hand heating is that T_{fing} and T_{toe} remained comfortable (T_{fing} : average of $30.9 \pm 0.9^{\circ}\text{C}$ during dexterity tests and an average of $35.3 \pm 0.2^{\circ}\text{C}$ during the inactive periods; T_{toe} : average of $30.5 \pm 0.9^{\circ}\text{C}$ during 3 h) without the use of any direct auxiliary hand/foot heating devices that are

prone to wear and tear during repetitive work in the cold. Electrically heated insoles/socks can also be problematic because the feet may be comfortable when an individual sits in the cold, but the feet may be too hot when pressure is applied to the sole of the foot by standing (22). Indirect hand heating can also maintain finger dexterity and finger comfort even when the hands are bare at -25°C for 3 h (2). This allows a soldier to perform fine finger dexterity work, while minimizing/eliminating the risk of frostbite. Brajkovic et al. (4) found that finger dexterity decreased by 60% when gloves were worn compared with bare hands when the PP test was done by subjects during exposure to -25°C air. This is in agreement with the finding of Havenith and Vrijkotte (20) that finger dexterity decreases by up to 70% when gloves are worn compared with bare-handed performance.

The final advantage of indirect hand heating is that heat loss from the body is decreased substantially, and hence this prevents a rapid decrease in H_b . A faster decrease in H_b (which occurred in the heated gloves condition) may put an individual at a greater risk for frostbite in the lower extremities or the upper extremities, if the gloves should malfunction. That is, a lower H_b would result in a lower Q_{fing} , and, therefore, a lower T_{fing} would be maintained. In addition, a lower H_b would impair cold-induced vasodilation response (9).

The main disadvantage of indirect hand heating is the higher power consumption required (111 ± 3 W to keep the skin under the electrically heated vest at $42 \pm 0.5^{\circ}\text{C}$) relative to using electrically heated gloves (14 ± 3 W required to keep T_{fing} at $34.1 \pm 0.4^{\circ}\text{C}$, if Arctic mitts are worn over the gloves; or 34 ± 3 W to keep T_{fing} at $29.2 \pm 1.1^{\circ}\text{C}$, if no mitts are worn over the gloves).

Conclusion. The key finding in this study was that during a 3-h exposure in the cold (-25°C), finger dexterity can be maintained during prolonged work (two 30-min work sessions) despite a low Q_{fing} if T_{fing} is maintained at a relatively high level (28 – 35°C), and $T_{\text{mus}} \geq 30^{\circ}\text{C}$ and ΔH_b greater than or equal to -472 ± 18 kJ. Dexterity decrements would have most likely occurred despite a T_{fing} of 28 – 35°C , if ΔH_b , T_{sk} , or T_{mus} were low enough, but neither a ΔH_b , T_{sk} , and T_{mus} of -472 ± 18 kJ, $28.5 \pm 0.3^{\circ}\text{C}$, and $29.8 \pm 0.5^{\circ}\text{C}$, respectively, were low enough to affect finger dexterity. All the above variables must be considered when passive, direct, or indirect forms of hand heating are examined in any study to properly determine the mechanism by which finger dexterity is maintained or hampered under different ambient and clothing conditions.

Overall, despite the fact that finger dexterity was maintained as effectively by using direct hand heating as it was by using indirect hand heating, the latter may be considered a superior method of maintaining dexterity in the cold in that the toes and deep body are kept warm, and tasks can be done comfortably bare-handed, among other benefits. The primary drawback to indirect hand heating is the greater heater power requirement.

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